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## CONTROLLABLE INTEGRATOR

## FIELD OF THE INVENTION

This invention relates to integrators and more particularly to circuitry in an integrated circuit that controls frequency response characteristics over a wide range of frequencies with adjustable capacitance and controllable transconductance.

## BACKGROUND OF THE INVENTION

Circuit components formed in integrated circuits commonly exhibit wide variations in operating characteristics attributable to variations in the semiconductor processes that form the integrated circuit of such components. By traditional design practices, additional or redundant components may be formed in an integrated circuit during the processing phase, and such additional components may thereafter be connected in or out of a circuit using a laser beam to selectively sever connecting links as required to adjust the operating characteristics of the circuit. Alternatively, signal controllable switches may be incorporated into the design of the integrated circuit to selectively connect additional components in response to externally applied control signals. However, such switches are not ideal in that they incorporate appreciable resistance into a circuit in the conductive state which can be detrimental to high frequency operating characteristics of the integrated circuit.

## SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, additional capacitive components may be selectively switched into circuit configuration in response to external control signals without introducing significant resistance with the capacitive components. In addition, controllable gain elements may be selectively controlled to amplify the effectiveness of capacitive components in the circuit for a wide range of operating frequency characteristics of the circuit as selectively configured.

## DESCRIPTION OF THE DRAWINGS

FIG. 1 is a circuit diagram of a conventional transconductance integrator;

FIG. 2 is a circuit diagram of one embodiment of the present invention;

FIG. 3 is a graph illustrating the operating characteristics of a transconductance amplifier; and

FIG. 4 is a circuit diagram of another embodiment of the present invention for providing wide dynamic control of operating frequency characteristics of the composite circuitry.

## DETAILED DESCRIPTION OF THE INVENTION

Referring now to FIG. 1, there is shown a conventional integrator including a differential pair of gain stages 9, 11 such as field-effect transistors having control electrodes, or gates, coupled to receive control signals applied to inputs 13, 15. The source electrodes, or sources, of the gain stages are coupled together and to a controllable current source 17, and each of the drain electrodes, or drains, is coupled to a controllable current sources 19, 21 and to one or more capacitive elements 23, 25. The sum of the current sources 19, 21 is usually set equal to the current from source 17. Selected ones of the capacitive elements may be coupled to

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ground, for example, via links that may be removed via laser-beam machining to alter the operating frequency characteristics of the circuit. Alternatively, semiconductor switches may be substituted (not shown) for the links to facilitate control of capacitance in the circuit in response to externally applied signals. However, such semiconductor switches commonly introduce significant resistance along with capacitance thus switched into the circuit, and this adversely affects high frequency operating characteristics of the circuit thus configured.

In accordance with one embodiment of the present invention, one or more differential pairs of capacitive elements are formed for selective connection into the circuit in response to an applied control signal. Specifically, as shown in FIG. 2, each capacitive element is formed as a pair of gain elements 27, 29 such as insulated-gate field-effect transistors with source and drain connected in common as one capacitive electrode and with the gate forming another capacitive electrode. The source-drain connections are connected in common to a control switch 31 that may also include a gain element responsive to an applied control signal for switching in or out the differential pair of capacitive components 27, 29. Specifically, at low-level applied control signal appearing on control input 33 (representative of the ON condition for NMOS type transistors 27, 29) the source-drain connections form conductive channels in the region of the respective gates in known manner to form capacitive components differentially connected across the outputs of the gain stages 35, 37. Thus, for each capacitive component of capacitance C, the differential connection of such components yields C/2 capacitance, without the equivalent resistance 39 of a control switch (in the biasing circuit) affecting the capacitance in the circuit thus configured. At high-level applied control signal appearing on control input 33 (representative of the OFF condition for NMOS type transistors 27, 29), wide depletion regions form adjacent the sources-drains, or essentially no channels form in the vicinities of the gates to contribute only a small fraction of the original capacitance introduced into the circuit. One or more banks of differentially connected capacitive components, each controlled by such bias-adjusting switching circuitry, may be provided to facilitate adjustment or control of the frequency response characteristics of the circuit thus configured.

Referring now to FIG. 3, there is shown a graph of the transfer function of the differential amplifier of FIG. 2 that includes gain elements 35, 37 and current sources 41, 43, 45 connected as shown. Specifically, as the differential of the control voltages 47, 49 applied to the control electrodes increases, the differential of drain currents  $I_1, I_2$  ( $\Delta I = I_1 - I_2$ ) increases, as shown by the curve 51. In the semiconductor amplifier circuit of FIG. 2, the sum of the drain currents 41, 43 substantially equals the combined current 45, and reducing these current levels typically alters the transfer function of the semiconductor amplifier, as shown by curve 53. The range of control voltages 55 over which the transfer function remains substantially linear diminishes with reduced current levels, as illustrated with reference to curve 53. Thus, at low levels of the combined source currents through current source 45, the substantially linear range of the transfer function on applied control voltages is narrow, and widens 55 with increased current levels. However, for a given level of the combined currents through source 45, significant increases in applied signal voltages appearing at inputs 47, 49 introduces significant non-linearity in the transfer function for operation at applied signal levels beyond the substantially linear range 55.

In accordance with another embodiment of the present invention, a plurality of amplifiers similar to the amplifier of